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Non-Determinism and the Dynamics of Knowledge

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Abstract
In this paper we attempt to shed light on the concept of an agent’s knowledge after a non-deterministic action is executed. We start by making a comparison between notions of non-deterministic choice, and between notions of sequential composition, of settings with dynamic and/or epistemic character; namely Propositional Dynamic Logic (PDL), Dynamic Epistemic Logic (DEL), and the more recent logic of Semi-Public Environments (SPE). These logics represent two different approaches for defining the aforementioned actions, and in order to provide unified frameworks that encompass both, we define the logics DEL\textsuperscript{VO} (DEL+Vision+Ontic) and PDEL\textsuperscript{VE} (PDL+Vision+Epistemic operators). DEL\textsuperscript{VO} is given a sound and complete axiomatisation.

1 Introduction
The paper focuses on the dynamics of knowledge in environments where agents are aware of (possibly non-deterministic) actions that are executed, but data is distributed privately: Semi-Public Environments as they are called, more recently in [Grossi \textit{et al.}, 2016] and earlier in [van der Hoek \textit{et al.}, 2011]. By data being distributed privately we mean that the agent knows a and b, if and only if he knows \( \psi \) after executing just a and after executing just b. In DEL\textsuperscript{V}, an instance of (1) is

\[ [x!] (K_x \lor K_y) \land [y!] (K_x \lor K_y) \leftrightarrow [x! \lor y!] (K_x \lor K_y) \]

This property makes perfect sense; after being announced that \( x \), or being announced that \( y \), the agent at least knows one of the two to be true. Another interesting instance of (1), however, should arguably fail. That is what happens in SPE, where the following formula is \not valid let \( K_{w,x} \) be shorthand for \( K_x \lor K_{x \sim x} \), and \( x:=\bot \) (respectively, \( \top \)) stands for the action of setting variable \( x \) to false (respectively, true):

\[ [x:=\bot] K_{w,x} \land [x:=\top] K_{w,x} \leftrightarrow [x:=\bot \lor x:=\top] K_{w,x} \]

The failure of (1) in SPE also has an intuitive appeal: some part of a non-deterministic action is executed, but which part is actually performed is not necessarily revealed to the agent.

So, in contrast to what happens in DEL\textsuperscript{V} (or PDL extended with epistemic operators), it is \not the case that if the agent knows \( \psi \) after executing \( a \) and after executing \( b \), that he necessarily knows \( \psi \) after the execution of the non-deterministic choice between them.

A similar analysis applies to sequential composition. In the same fashion as before, we have the validity that essentially defines sequential composition in PDL:\textsuperscript{P}:

\[ [a \cdot b] \varphi \leftrightarrow [a] [b] \varphi \]

And in DEL\textsuperscript{V}, we have that formula \([x!] [y!] K_x \land y \leftrightarrow [x!] [y!] K_x \land y \) is a validity, for \( x, y \) being atoms. This is again intuitive: announcing \( x \land y \) ought to be the same as announcing \( x \) and then announcing \( y \). But also this schema is not valid in SPE: we very briefly refer to an example from [Grossi \textit{et al.}, 2016] below. In its perspective the failure of (2) should not come as a surprise.

Example 1 The agent can see only variable \( x \), and we execute the action where we non-deterministically toggle the values of \( x \) and \( y \), or just \( y \). After this action, we also non-deterministically toggle the value of \( x \), or of \( y \).

In both steps the agent can distinguish between the two possible actions; one changes \( x \), the other does not. Consider that the agent has the opportunity to observe the impact of the first action, before the second starts, and then the impact of the second. As a result, he can distinguish between any of the four total alternatives (where both \( x \) and \( y \), or just \( x \), or just \( y \), or nothing, was changed; for later use let us denote the four individual actions with \( v_1, v_2, v_3, v_4 \) respectively). But
what if the agent has no opportunity to observe what happened in-between? Then he can only observe what happened at the very end, and in our example, he will not be able to distinguish between all possibilities, particularly those with same truth value for $x$, but different for $y$.

The paper introduces and studies a logic that integrates both the above approaches to choice and composition, defining two novel action operators which we call opaque choice and composition. The proposed logic is a generalisation of both SPE and DEL and is called DELVO: DEL plus vision plus ontic change, which are features of SPE. Logic DELVO is then compared with an extension of PDL with vision and epistemic modalities we also introduce (called PDLVE). This logic can be considered the natural ‘abstraction’ of DELVO in PDL style, in the sense that the actions involved will be arbitrary connections between possible worlds (as opposed to the other dynamic logic, DLPAD [Balbiani et al., 2013], that uses assignments). The relationship between DELVO and PDLVE is studied in detail. The drawing below recapitulates the relations among the investigated logics.

### 2 Preliminaries

Throughout the paper, we will be dealing with a finite set $Ag = \{1, \ldots, n\}$ of agents, and a countable set of propositional variables $\forall var = \{x_1, x_2, \ldots\}$. A valuation $\theta : \forall var \to \{true, false\}$ assigns a truth value to each variable $x \in \forall var$. The set of all valuations is denoted by $\Theta$. Given a relation $R \subseteq A \times A$, $R^-$ is its reflexive, symmetric, and transitive closure. For $S \subseteq A$, $R(S) = \{w \in A \mid \exists v \in S \text{ s.t. } vRw\}$.

Let us next give a summary of the notation for the different classes of models we will be using, given that several logics are involved in this study.

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<th>Static Models</th>
<th>DELVO</th>
<th>PDL</th>
<th>DELVE</th>
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<tr>
<td>Dynamic Models</td>
<td>$\mathcal{E}M$</td>
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<td>$\text{PM}$</td>
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A model $M$ from any of the above classes, has a set of worlds/points $W$. We then have single-pointed models to be pairs of the form $(M, w)$, for $w \in W$, and multi-pointed models to be pairs of the form $(M, S)$, for $S \subseteq W$. We will use the prefix $\sigma$ or $\mu$, and the name of a class in brackets, to denote the corresponding classes of single-pointed and multi-pointed models (e.g., $\mu(A\text{M})$ stands for multi-pointed action models).

To justify the abbreviations: $\mathcal{E}M$ stands for Epistemic Models, $\mathcal{E}MV$ for the Epistemic Models with Vision, $\mathcal{DM}$ for Dynamic Models and $\mathcal{DE}M$ for Dynamic Epistemic Models, $\text{AM}$ for Action Models, AMT for Action Models with Toggle sets, PM for Program Models.

We recapitulate the basic notions of DEL, we refer the reader to [van Ditmarsch et al., 2007, Ch. 6] for a comprehensive exposition. Let $\mathcal{L}$ be a logical language for given parameters $Ag$ and $\forall var$. An action model $M$ is a tuple $(W, R, \varphi)$ such that $W$ is a finite set, $R : Ag \to 2^{W \times W}$ assigns an equivalence relation to each agent $i \in Ag.$ and $\varphi : W \to \mathcal{L}$. We will denote the class of action models for $\mathcal{L}_{\text{DEL}}$ with $\text{AM}$. Language $\mathcal{L}_{\text{DEL}}$ is given by syntax $\varphi ::= x | \neg \varphi | \varphi \land \varphi | K_i \varphi | [a] \varphi$, where $x \in \forall var$, $i \in Ag$ and $a ::= (M, w) | (a \cup a)$ where $w \in W$.

An epistemic model for $\mathcal{L}_{\text{DEL}}$ is $M = (W, R, f)$, where $W$ is a (possibly empty) set, the set of states $f : W \to \Theta$ assigns a valuation $\theta$ to each state in $W$; $R : Ag \to 2^{(W \times W)}$ assigns an equivalence relation to each agent $i \in Ag$. $\mathcal{E}M$ denotes the class of epistemic models. The model resulting from the application of an action model $M$ to an epistemic model $\mathcal{M}$, referred to here as model product, is the model $M \otimes \mathcal{M} = (W', R', f')$ such that $W' = \{(w, w') \in W \times W | M, w \models \varphi \}$, $(w, w')R'(w, u) \iff wRu$ and $wRu$, and $f(w, w') = f(w)$. Actions of $\mathcal{DEL}$ are defined by syntax $a ::= (M, w) | a \cup a$. Finally, for each action $a$, we have the induced relation $[a] : \{M, w \in \sigma(AM)\} \to \{M, w \in \sigma(AM)\}$ if $M, w \models \varphi$ and $(M', w') = (\otimes M, (w, w))$, while $[a \cup b] = [a] \cup [b]$. We have $M, w \models [a] \varphi$ iff for all $M'$, $w' \in [a](M, w)$ we have $M', w' \models \varphi$. The rest of the truth definitions are as usual.

Let us denote the actions of $\mathcal{DEL}$ with $\mathcal{L}^\text{Act}_{\text{DEL}}$. In the remainder of the section we define an equivalent presentation of $\mathcal{DEL}$ based on multi-pointed action models. This allows us to have a unified model structure to handle all actions of $\mathcal{L}^\text{Act}_{\text{DEL}}$, which facilitates later comparison with SPE. So let us consider the language $\mathcal{L}^\text{Act}_{\text{DEL}}$ where actions are only multi-pointed action models, that is, $a ::= M, S$ where $M, S \in \mu(AM)$; and the language of $\mathcal{DEL}$ using $\mathcal{L}^\text{Act}_{\text{DEL}}$ denoted by $\mathcal{DEL}_{\text{Act}}$. Now the induced relation is defined as $[M, S](M, w) = (M \otimes M, (w, w) | w \in S )$.

In what follows, “$\cup$” denotes the disjoint union of two action models, whose contexts for worlds are, for simplicity, already assumed to be disjoint.

**Definition 1 (Translation to $\mu(AM)$)** We define function $\tau : \mathcal{L}^\text{Act}_{\text{DEL}} \to \mathcal{L}^\text{Act}_{\mu(AM)}$ as follows: If $M, w \in \sigma(AM)$, then $\tau(M, w) = M, (w)$. If $a, b \in \mathcal{L}^\text{Act}_{\text{DEL}}$ and $\tau(a) = M_0, S_0$, $\tau(b) = M_0, S_0$, then $\tau(a \cup b) = M_0 \cup M_0, S_0 \cup S_0$.

The fact that this translation is truth-preserving is formally stated in the following Theorem.

**Theorem 1** For all $\varphi \in \mathcal{DEL}$ let $\tau(\varphi)$ denote the formula that is $\varphi$ but for each action $a$ all its occurrences in $\varphi$ are replaced by $\tau(a)$. For all $M, w \in \sigma(\mathcal{E}M)$ and $\varphi \in \mathcal{DEL}$, we have $M, w \models \varphi$ iff $M, w \models \tau(\varphi)$.

**3 The Logic DELVO**

The first traditional setting on which we would like to expand and incorporate both alternative versions of choice and composition mentioned in the introductory section is DEL. The difference in behaviour we have observed relies on vision—that is, what agents can observe—and ontic change—that is, the ‘factual’ differences among points of evaluation in the model. It thus seems reasonable to introduce a DEL-style logic, with epistemic models enriched with vision, and action models that allow for ontic change.

**Definition 2 (Toggling values)** Let $\theta \in \Theta$ and $S \subseteq \forall var$. The toggling of values for the variables in $S$ in $\theta$, notation $\downarrow S(\theta)(x)$, is the atomic valuation (member of $\Theta$) defined as $\downarrow S(\theta)(x) = not \theta(x)$ if $x \in S$, otherwise $\downarrow S(\theta)(x) = \theta(x)$. Given two sets of variables $S_1$ and $S_2$, we denote their symmetric difference by $S_1 \triangle S_2$, i.e., $S_1 \triangle S_2 = (S_1 \cup S_2) \setminus (S_1 \cap S_2)$. 

Definition 3 (DELVO Action Models) A (DELVO) action model is a tuple $M = ⟨W, R, \text{pre}, \text{tgl}⟩$, where $W ≠ ∅$ is finite, $R : Ag → 2^{(W × W)}$ assigns an equivalence relation to each agent $i ∈ Ag$, pre : $W → Ė$, tgl : $W → P(Var)$ and each tgl($w$) is finite. A pair $(M, S)$, where $M$ is an action model and $∅ ⊆ S ⊆ W$, is called a Multi-Pointed Action Model. When clear from context, instead of $M, \{w\}$ we may also write $M, w$. The class of all action models is denoted by $\mathcal{AMT}$.

In comparison with the standard manifestation of post-condition effects in DEL, which uses assignments (see for example [van Benthem et al., 2006]), our action models use toggle sets, as in [Grossi et al., 2016]. The reason is that it allows for a more elegant handling of the notion of vision, since the agent successfully resolves uncertainty based on the difference in ontic changes caused by the actions. The two formulations are technically equivalent: one can simulate ‘assignments’ to variables using toggle sets [Grossi et al., 2016]. Pairs $(M, S)$ now are essentially the multi-pointed action models of DEL, but with each point $w$ carrying additional information about a finite toggle set tgl($w$). Finally the syntax of formulas $ϕ ∈ \mathcal{DELVO}$ is:

$$ϕ ::= T | x \in V, x | ¬ϕ | ϕ ∧ ϕ \mid | [M, S]ϕ | R_iϕ$$

where $x ∈ Var$, $i ∈ Ag$, $(M, S) ∈ \mathcal{AMT}$.

Definition 4 (DELVO models) An epistemic model (with vision) $M$ for $\mathcal{DELVO}$ is a tuple $M = ⟨W, R, f⟩$ where $⟨W, R, f⟩ ∈ \mathcal{EMV}$, $V : Ag → 2^{Var}$, and

- $wR_iu$ implies ($f(w) ∩ f(u)$) $∩ V(i) = ∅$.

$\mathcal{EMV}$ denotes the class of epistemic models with vision. The set of all vision functions $V$ is denoted by $\mathcal{Vis}$.

So the models of DELVO are standard epistemic models enhanced with a vision function recording information about which propositional variables each agent observes. If an agent considers two worlds indistinguishable, then it must be the case that he cannot observe a difference in their valuation.

There exists the possibility that the indistinguishability relation of an action model is not compatible with the vision function of an epistemic model. The way we address these cases when trying to create a model product, is by ‘rewiring’ the action models to be ‘in sync’ with the agents vision, but without them hiding any information at all, or giving information not acquired by vision.

Definition 5 Let $V ∈ \mathcal{Vis}$ and $M ∈ \mathcal{AMT}$. We define the action model $M^V = ⟨W^V, R^V, \text{pre}^V, \text{tgl}^V⟩$ as follows:

- $W^V = W$; $\text{pre}^V = \text{pre}$; $\text{tgl}^V = \text{tgl}$:
- $wR^V_iu$ iff $wR_iu$ and $(\text{tgl}(W^V) \cup \text{tgl}(u)) \cap V(i) = ∅$.

Now that we have everything else in place, we proceed to define the semantics of formulas and actions in DELVO.

Definition 6 Let $M = ⟨W, R, V, f⟩ ∈ \mathcal{EMV}$. The truth conditions are as for DEL, plus $(M, w) ∈ V_i$ iff $x ∈ V(i)$.

Relation $[M, S] ∈ (\mathcal{EMV}) × (\mathcal{EMV})$ is defined again as in DEL: $(M, S) \models (M ⊕ M, (w, w))$ in $S$, while $(M ⊕ M)$ is now the epistemic model $M'$ ($W', R', V', f'$) defined as:

- $W' = \{w, w\} | w ∈ W, w ∈ W$ & $(M, w) ≡ \text{pre}(w);$  
- $(w, w)R'_i(u, u)$ iff $wR_iu$ and $wR^V_iu$;
- $V' = V, f'(w, w) = θ(\text{tgl}(w)) (f(w))$.

We conclude the section thus far by introducing a notion of bisimulation between DELVO models [Blackburn et al., 2001].

Definition 7 Let $M, M' ∈ \mathcal{EMV}$. A non-empty relation $Z ⊆ W × W'$ is a bisimulation iff for all $(w, w') ∈ Z$ and $i ∈ Ag$: For $∀ x ∈ Var$, $x ∈ f(w)$ iff $x ∈ f(w')$, and $x ∈ V(i)$ iff $x ∈ V'(i)$; Forth $∀ w ∈ W$, if $wR_iw$ then there is a $w' ∈ W'$ such that $wR_iw'$ and $(w, w') ∈ Z$; Back $∀ w' ∈ W'$, if $w'R_iw'$ then there is a $w ∈ W$ such that $wR_iw$ and $(w, w') ∈ Z$. Two multi-pointed action models $(M, S)$ and $(M', S')$ are bisimilar (written $(M, S) ≃ (M', S')$) iff there is a bisimulation $Z$ between $M$ and $M'$, such that for any $w ∈ S$, there is a $w' ∈ S'$ with $(w, w') ∈ Z$, and vice versa.

Axiomatisation The axiomatisation for DELVO is comprised of the axioms and rules for logic $\mathcal{SSV}$, axioms for vision $Vx → (Kx ∨ K¬x)$ and $Vx → Kx[\omega, s]$, and reduction axioms that allow any formula that includes dynamic modalities to be reduced to one that does not. These reduction axioms are identical to those of $\mathcal{SSV}$ (Grossi et al., 2016), except the slightly changed reduction action for knowledge: $(M, w)[ϕ, v] ↔ (\text{pre}(w) → A_{V ∈ V} \{ϕ → ϕ\}, K_i[ϕ, v]),$ with $\text{K}_i$ being a characteristic formula of vision function $V$ over the variables that appear in $M$. Soundness is derived easily from the definitions, and completeness is proven along the lines of DEL and $\mathcal{SSV}$ via the standard reduction technique; completeness is then further reduced to that of logic $\mathcal{SSV}$, that is, the multi-agent epistemic logic $\mathcal{SSV}$, [Fagin et al., 1995], with the two additional axioms for vision.

Opaque Choice and Composition The logic DELVO provides us with a setting in which to properly capture not only the traditional forms of choice and composition (cf. Theorem 1) but also their opaque variants—opaque choice and composition—we motivated in the introductory section.

Let the set of actions $Act$ be defined inductively as:

- For $∀ a ::= ϕ \mid ϕ \mid \exists x \mid a ⊔ a \mid a \cdot ω \mid a ; a \mid a ; a$, where $ϕ ∈ \mathcal{L}$, $x ∈ Var$ and $T ⊆ Ag$.

The constructs $⊕$ and $;$ denote the opaque variants of the standard $⊎$ and $;$. For $T = Ag$ we write $ω$ omitting the subscript. Each of the above actions we recursively define in terms of suitable DELVO action models. By writing action “$a$” in a formula we will mean the multi-pointed action model that corresponds to $a$.

Definition 8 1. (Announcement) Let $M_{ϕ} = ⟨W, R, \text{pre}, \text{tgl}⟩$, where $W = \{e\}$, $R_i = \{(e, e)\}$, $\text{pre}(e) = ϕ$ and $\text{tgl}(e) = \{\}$. The multi-pointed action model for $ϕ$ is $M_{ϕ} = (e)$.

2. (Toggle) Let $M_{x} = ⟨W, R, \text{pre}, \text{tgl}⟩$, where $W = \{t\}$, $R_i = \{(t, t)\}$, $\text{pre}(t) =$ $T$ and $\text{tgl}(t) = \{x\}$. The multi-pointed action model for $x$ is $M_{x} = \{t\}$.

3. (Test) Let $M_{ϕ} = ⟨W, R, \text{pre}, \text{tgl}⟩$, where $W = \{w\}$, $R_i = W × W, \text{pre}(w) = ϕ, \text{pre}(v) = ¬ϕ$ and $\text{tgl}(w) = \text{tgl}(v) = \{\}$. The multi-pointed action model for $ϕ$ is $M_{ϕ} = ⟨w⟩$.

In order to define test as a multi-pointed action model, we have based ourselves on the archetype that the test relation
The action model for standard non-deterministic choice is a disjoint union of action models, as in Definition 1.

Definition 9 (Opaque Non-det. Choice) Let \( a, b \in \text{Act} \).

The action model for \( a \uplus b \) is \( M_{a,b} = S_{a,b} \uplus \rho_{a,b} = \{ W', R' \}, \rho' \}, S' \) where, if \( M_{a,b}, S_{a,b} = (W, R, \text{pre}, \text{tgl}) \), \( S : \)

- \( W' = W; \text{pre}' = \text{pre}; \text{tgl}' = \text{tgl}; S' = S \)
- For \( i \in T \), \( R'_i = (R \cup (S' \times S'))^- \)
- For \( i \notin T \), \( R'_i = R_i \).

The intuition behind opaque choice compared to standard choice is that, for agents in \( T \), it ‘overrides’ any information gained by the distinction between points in \( S \). It can be read as “non-deterministically execute one of the action points in \( S \), but, after execution you will only be able to tell between them if your vision allows it”. To do this, we simply take the action model of the standard non-deterministic choice, and then connect, for the agents in \( T \), the worlds in \( S \). As mentioned earlier, an agent’s uncertainty is bound by the information it acquires by vision (recall \( M \odot M \) in Def. 6).

Example 2 Consider the epistemic model \( M \) with a single world \( w \) with \( x \in V(1), x \notin V(2) \). In Figure 1 we compare the action models \( \{ x \uplus T \} \) and \( \{ x \urcorner T \} \), along with the resulting model products. Note that for opaque choice, \( M, w \models [\{ x \urcorner T \}]Kw_2w \) while for standard choice \( M, w \models [\{ x \urcorner T \}]Kw_2w \). And for agent 1 that ‘sees’ \( x \) we have \( M, w \models [\{ x \urcorner T \}]Kw_2w \), and \( [\{ x \urcorner T \}]\neg Kw_2w \).

This example demonstrates that both directions of validity (1) fail for opaque choice. Indeed, we have \( M, w \models [\{ x \urcorner T \}]Kw_2w \land [\{ x \urcorner T \}]\neg Kw_2w \), and similarly \( M, w \models [\{ x \urcorner T \}]\neg Kw_2w \) but \( M, w \models [\{ x \urcorner T \}]Kw_2w \).

The uncertainty of the agent described by the intuition above and portrayed by this example can be described more generally by the following formula: let \( (M, w), (M', w') \in \mu(\text{AMT}) \) and \( V \) be the vision function for which agent i can see the variables in \( \text{tgl}(w) \) and \( \text{tgl}(w') \).

Then we have:

\[
\begin{align*}
\chi_V \land [M, w \models M', w', \neg \chi_V] \land (\text{pre} \rightarrow \text{pre'})
\end{align*}
\]

We now move on to the subject of sequential composition, which poses some more difficulties. It becomes evident that it is not possible to define regular composition only as a function of the models \( M_a, M_b \), without vision as a parameter; this is in contrast with the action models and the other constructs defined so far. As proof recall the actions of Example 1: if \( V(i) = \emptyset \) then \( v, w, v_k^2 \) for \( 1 \leq j, k \leq 4 \) in the action model, and for the resulting worlds also \( (w, v), R_i(w, v_k) \). If we set \( V(i) = \{ x \} \) then the action model would be the same but it should not be the case e.g. that \( (w, v_2), R_i(w, v_3) \). We are therefore led to the following definition.

Definition 10 (Composition) Let \( V \in \text{Vis} \), \( M_a = (W_a, R_a, \text{pre}_a, \text{tgl}_a), S_a \) and \( M_b = (W_b, R_b, \text{pre}_b, \text{tgl}_b), S_b \). Their composition w.r.t. \( V \) is the pointed action model \( M_{a,b} = \{ W, R, \text{pre}, \text{tgl} \}, S \) where: \( W = W_a \times W_b, S = S_a \times S_b \).

- \( (w, w'), R_i(v, v'), v \) iff \( w, v \in R_i(v, v') \wedge v \wedge R_i(v, v') \)
- \( (w, v), (w, v) = (M_a, w), (w, v), v \) iff \( tgl_i(w), tgl_i(v) \)

We need not advocate the correctness of the definition regarding \( W, \text{pre}, \text{tgl} \), and \( S \), as they are what is expected for the composition of two action models in DEL as well as SPE. Vision influences only the accessibility relation \( R \), and regarding that we need only note that it is again the one normally expected, with the exception that the agent has the opportunity to apply his vision after execution of actions \( a \) and \( b \). Hence \( R_i^V \) is used (Def. 5) and not \( R_a \). Finally, let us point out that with this definition a vision function \( V \) is linked to an action model directly, and an epistemic model \( M \) may have a vision function \( V' \neq V \). In that case, a formula using such an action model cannot be interpreted in \( M \).

We do not run into the same kind of problem with opaque composition as it uses the same idea behind opaque choice: it disregards previous connections (or more precisely, the lack thereof) in Intuitively speaking, the agent is absent while actions \( a \) and \( b \) are executed, ‘missing’ any announcements made and also the opportunity to apply his vision as changes occur to the variables.

Definition 11 (Opaque Composition) Let \( a, b \in A \). The pointed action model for \( a; b \) is \( M_{a,b} = (W, \text{pre}, \text{tgl}), S \) defined as in Definition 10 but \( R_i = W \times W \).

We can now see how to falsify property (2) from the introduction. Consider again the epistemic model of Example 2. Action model for \( \{ x \uplus T \} \); \( T \uplus T \) is the action model of \( \{ x \uplus T \} \), found in the first row of Figure 1, while in the second row we have the action model of \( \{ x \uplus T \} \) and the resulting epistemic model. Applying action \( T \) does not change anything, and so \( M, w \models [\{ x \uplus T \}]T \) while \( M, w \models [\{ x \uplus T \}]T \).

Relation to DEL and SPE Not coincidentally, the class of DELVO (static) models—i.e. epistemic models with vision—is exactly the class of models of SPE, and subsumes the class of standard epistemic models (without vision, that is, where vision is empty), which are the models of DEL. In this section we define the relevant translations among these classes of models and state, without proof, and state the two truth-preserving embeddings.

Definition 12 We define function \( h : \text{EM} \rightarrow \text{EMV} \) as follows: Let \( M = (W, R, F) \in \text{EM} \). Then \( h(M) = (W, R, V, F) \), where \( V \) is such that for all \( i \in AG, V(i) = \emptyset \).
We denote the formula that is \( \varphi \) but for each action a all its occurrences in \( \varphi \) are replaced by \( g(a) \). Let \( M, w \in \sigma(E,M) \) and \( \varphi \in L_{D} \). We have \( M, w \models \varphi \iff \Pi(h(M), w) = g(\varphi) \).

We work similarly for SPE; its models are exactly those of DELVO, and its action models can be seen as a special case of DELVO action models.

We define function \( f: \sigma(P(M)) \rightarrow \mu(A) \) as follows: Let \( M = \{ w_{1} = (\varphi_{1}, X_{1}), \ldots, w_{n} = (\varphi_{n}, X_{n}) \} \subseteq PM \) and \( w \in M \). Then \( g(M, w) = \{ (W, \text{pre}, \{ w \}) \mid W = \{ w_{1}, \ldots, w_{n} \}, \text{pre}(w_{i}) = \varphi_{i} \text{, } \text{tgl}(w_{i}) = X_{i} \text{, and } R_{j} = W \times W \} \).

We now attempt a generalisation of epistemic choice and composition to a more abstract PDL-like setting. For DELVO, a large part of the intuitions and formal techniques stem from the use of action models. The latter do not exist in PDL and it is interesting to examine how it would be possible to circumvent the use of action models. The latter do not exist in PDL but also extent their use to a richer paradigm, but also extent their use to a richer class of actions.

With \( \Pi(E) \) we attempt not only to represent the action constructs in the PDL paradigm, but also extend their use to a richer class of actions.

In addition to sets \( Ag \) and \( Var \), let also a countable set of atomic actions \( Atom = \{ a_{1}, a_{2}, \ldots \} \) be given.

The language of \( \Pi(E) \) is defined by the following syntax:

\[
\varphi ::= \top \mid x \mid V[w] \mid \neg \varphi \mid \varphi \land \varphi \mid \{ \alpha \} \varphi \mid K_{\phi} \varphi
\]

where \( a ::= \pi \in \text{Atom} \mid a \cup a \mid a \cup \alpha \mid a \cup \alpha \mid a \cup \alpha \mid a \cup \alpha \mid a \cup \alpha \).

To capture epistemic choice in \( \Pi(E) \) we rely on the basic intuition behind it. Given actions \( a, b, \) and world \( w \), “either \( a \) or \( b \) is executed at \( w \), but the agent does not know which, unless his vision allows him to do that”. Based on the above, we first give an auxiliary definition: given \( M \in E(MV) \) and relations for \( a, b, \) in \( \Pi(E) \), this definition describes a representation of the epistemic model that should be the image of \( a \circ b \).

Let \( M = (W, R, V, f) \in E(MV) \). For \( S \subseteq W \) let \( N(S) \) denote the epistemic submodel generated by \( S \), and \( N_{w}(S) \) denote the worlds of that model. We remind that for \( E \subseteq W \times W \), \( E(S) = \{ w \in W \mid \exists w' \in S \text{ s.t. } wRw' \} \).

We now have two logics for describing knowledge, and epistemic & ontic change. A natural question is whether the actions of \( \Pi(E) \) are more general than those of DELVO. We find that, under mild restrictions, they are not.

As one would expect, the transition from DELVO to \( \Pi(E) \) can be done simply enough. After all \( DELVO \) can be reduced to \( S5 \), and epistemic models with vision are part of \( \Pi(E) \) models. To evaluate a given \( DELVO \) formula \( \varphi \) in a model \( M, w \in \sigma(E(MV)) \), one would have to potentially evaluate subformulas of \( \varphi \) in \( M \) and in the respective model products.
The idea for the transition from del to pOLVE, is to define a single pOLVE model by putting together all such models.

**Definition 17** Let $M \in \sigma(\mathcal{E}, \mathcal{M}V)$ and $\varphi \in \mathcal{PDL}_{\mathbf{E}}$ (M may be omitted when clear from context) by induction on the complexity of $\varphi$ as follows: $T_i(\top) = T_i(x) = T_i(V(x) = \{M\})$, $T_i(\neg \varphi) = T_i(K_i \varphi) = T_i(\varphi)$, $T_i(\varphi \land \psi) = T_i(\varphi) \cup T_i(\psi)$. Then it holds that $\exists \varphi \in \mathcal{PDL}_{\mathbf{E}}$ such that $\varphi$ is a function such that $\varphi(w) \models t \iff T_i(\varphi)$, but for all action models $M, S_i$, that appear in $\varphi$, all its occurrences are replaced with $S_i$. Then it holds that $M, w \models \varphi$ iff $T_i(\varphi)$, $w \models t(\varphi)$.

For the direction “pOLVE to del”, the problem we will be trying to solve is, given $M, w \in \sigma(\mathcal{E}, \mathcal{M})$ and $\varphi \in \mathcal{PDL}_{\mathbf{E}}$, is there a translation $t$ for $\varphi$, where actions of PDL have been translated into multi-pointed action models, such that $N(w), w \models t(\varphi)$? Such a translation is impossible to define homogeneously for all models of PDL, as action a changes depending on its relation, in each pOLVE model $M$. So let $M \in \mathcal{E}, \mathcal{M}$, and $a \in \mathbf{A}$. Action $a$ is perhaps executable in a number of worlds, and for each such world, the action may have a number of different possible executions. When focusing on the case where a single world $w$ is connected through a with a world $v$, then the question is: is there a multi-pointed action model to transform $N(w)$, $w \rightarrow N(v)$, $v$?

This question relates to epistemic planning, which is undecidable for the multi-agent case [Aucher and Bolander, 2013], and it has been answered in [van Ditmarsch and Kooi, 2008] for finite $\mathbf{s}$ models (and other models under certain restrictions) and using action models with assignment to achieve ontic change. Our construct will follow the same idea, but we will be focusing on pOLVE models that (i) have finite $\mathbf{W}$, (ii) are an epistemic bisimulation contraction (cf. [Blackburn et al., 2007]), and (iii) for which $w \rightarrow v$ implies that for all $w' \in N(w), f(w) \Delta(f(w')$ is finite.

Note that for any $M, w \in \sigma(\mathcal{E}, \mathcal{M})$ satisfying (i)-(iii), there exists a characteristic formula $\varphi_w \in \mathcal{PDL}_{\mathbf{E}}$ such that $w \models \varphi_w$. We define $h(M, w, v) = (w, R, pre, tgl) \in \mathbf{AMT}$ as:

- $W = N(w), R = R|_{N(w)}$;
- for all $w \in W, pre(w) = \varphi_w, tgl(w) = f(w) \Delta f(w)$.

Back to the more general problem: action $a$ can lead a world $w$ to a multitude of worlds $v_i$, finite in number. A way to get an equivalent result by using action models, is to put ‘side by side’, via disjoint union, models $h(M, w, v_i)$. Furthermore, we can have the case where action $a$ is executable in a multitude of worlds $w_j$, again finite in number. Again, this can be solved by taking the disjoint union of $h(M, w_j, v)$.

**Definition 19** Let $M, w \in \sigma(\mathcal{E}, \mathcal{M})$ and $\varphi \in \mathcal{PDL}_{\mathbf{E}}$ and a an action that appears in $\varphi$. Let $M$ satisfy (i)-(iii). Define:

- $M_a, S_a = \bigcup_{w \in M} \bigcup_{w \in E_a(w)} h(M, w, v)$, $v$.

**Theorem 6** Let $M, w \in \sigma(\mathcal{E}, \mathcal{M})$ as above and $\varphi \in \mathcal{PDL}_{\mathbf{E}}$. Let $t : \mathcal{PDL}_{\mathbf{E}} \rightarrow \mathcal{DEL}$ be a function such that $t(\varphi)$ is $\varphi$, but for all actions “a” that appear in $\varphi$, all its occurrences are replaced with $M_a, S_a$. Then it holds that $M, w \models \varphi$ if $N(w), w \models t(\varphi)$.

**5 Conclusion**

We pointed to two different ways to understand the interaction between knowledge dynamics and non-determinism, starting from logics del, pDL, and SPE. We presented a multi-pointed action model formulation of del to express non-deterministic choice. We defined the logic del, which is capable of handling epistemic and ontic change (for del-based work that also combines epistemic and ontic change see [van Eijck, 2004a; 2004b], [van Benthem et al., 2006], and [van Ditmarsch and Kooi, 2008]), along with the notion of vision, and allows for a richer set of actions than those of del and SPE. Within del, we defined both standard and opaque forms of choice and composition. We also provided a sound and complete axiomatisation for it, and a number of embedding results situating it among its related formalisms.

We also explored a more abstract logic, capable of epistemic and ontic change, with an even richer class of actions: pOLVE. Its semantics are based on pDL models with epistemic relations and vision atoms. Here, our contribution is the definition of opaque non-deterministic choice and composition in this pDL-like setting. Finally, we provided theorems that compare del and pOLVE, thus also investigating the relation between action models, and atomic actions defined arbitrarily.

Several opportunities for future work exist; we briefly mention that for del we would like vision atoms to exist for other formulas as well, not only variables. For pOLVE there is the obvious need for a proof system. Furthermore, two papers that in our opinion are especially relevant are [van Eijck, 2012] and [Charrier et al., 2016]. The former distinguishes between actual use of vision and the capability to use it. In the latter, vision is necessarily common knowledge and the notions of higher order and joint vision are introduced. One may also consider the agents not being aware of the actions being executed or some of the variables [van Ditmarsch et al., 2012]. Another worthwhile endeavour would be a systematic comparison between our framework and the Situation Calculus (cf. [Schfer and Levesque, 2003; van Ditmarsch et al., 2011]) and the standard and opaque variants. The difference between the variants is demonstrated by the difference between MDP and POMDP (see for example [Boutilier et al., 2000; Delgrande and Levesque, 2013] and [Bacchus et al., 1999]).

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References


